

Chesapeake Inundation Prediction System (CIPS): A Regional Prototype for a National Problem

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Abstract-Recent Hurricanes Katrina and Isabel, among others, not only demonstrated their immense destructive power, but also revealed the obvious, crucial need for improved storm surge forecasting and information delivery to save lives and property in future storms. Current operational methods and the storm surge and inundation products do not adequately meet requirements needed by Emergency Managers (EMs) at local, state, and federal levels to protect and inform our citizens. The Chesapeake Bay Inundation Prediction System (CIPS) is being developed to improve the accuracy, reliability, and capability of flooding forecasts for tropical cyclones and non-tropical wind systems such as nor'easters by modeling and visualizing expected on-land storm-surge inundation along the Chesapeake Bay and its tributaries. An initial prototype has been developed by a team of government, academic and industry partners through the Chesapeake Bay Observing System (CBOS) of the Mid-Atlantic Coastal Ocean Observing Regional Association (MACOORA) within the Integrated Ocean Observing System (IOOS). For demonstration purposes, this initial prototype was developed for the tidal Potomac River in the Washington, DC metropolitan area. The preliminary information from this prototype shows great potential as a mechanism by which NOAA National Weather Service (NWS) Forecast Offices (WFOs) can provide more specific and timely forecasts of likely inundation in individual localities from significant storm surge events. This prototype system has shown the potential to indicate flooding at the street level, at time intervals of an hour or less, and with vertical resolution of one foot or less. This information will significantly improve the ability of EMs and first responders to mitigate life and property loss and improve evacuation capabilities in individual communities. This paper provides an update and expansion of the initial prototype that was presented at the Oceans 2006 MTS/IEEE Conference in Boston, MA.

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I. INTRODUCTION

Recent Hurricanes Katrina in the Gulf of Mexico and Isabel in the Chesapeake Bay, in 2005 and 2003 respectively, not only demonstrated immense destructive power, but also revealed the obvious, crucial need for improved storm surge forecasting and information delivery to save lives and property in future storms. Atmospheric models have developed significant skill in predicting storm development, movement, and intensity, yet the hydrodynamic modeling capability to predict and visualize flooding remains limited. This is especially relevant when combined effects of wind-driven ocean storm surge, tides, and downriver discharge lead to rapid, intense flooding.

To pursue this need for a better inundation prediction system, a team of U.S. government (federal, state, and local), academic, and industry organizations has been developing the initial prototype Chesapeake Inundation Prediction System (CIPS) as a potential tool for the U.S. National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) Weather Forecast Offices (WFOs) to better support Emergency Managers (EMs) who protect and serve citizens throughout the Chesapeake Bay watershed area. The architecture of CIPS is being designed for potential replication in other coastal and Great Lakes regions with local participants and their models and capabilities. CIPS is an initiative of the Chesapeake Bay Observing System (CBOS) within the Middle Atlantic Coastal Ocean Observing Regional Association (MACOORA) of the Integrated Ocean Observing System (IOOS) in coordination with the Chesapeake Research Consortium (CRC). This paper reports the development of this work since the presentation of *An Integrated Coastal Observation and Flood Warning System: Rapid Prototype Development* at the Oceans 2006 MTS/IEEE Conference in Boston, MA.

The WFO Sterling, VA and Noblis (formerly Mitretek Systems) had discussed the challenge of predicting Potomac River storm surge and flooding inundation in the metropolitan Washington, DC region earlier in the summer of 2005. Within this area, cities such as Alexandria, VA, experience flooding related to storm surge, tides, and river discharge from tropical storms and nor'easters transiting the Chesapeake Bay. Hurricane Isabel dumped several inches of rain in the upper Potomac River watershed, and subsequent downstream flooding along the river was expected. What would not have been typically anticipated was the approximately 6-8 foot storm surge that moved some 120 miles upstream from the Bay along the relatively narrow and winding river. The surge caused significant flooding in Old Town Alexandria and neighboring communities, damaged thousands of homes and businesses, and created losses in the tens of millions of dollars to homes and businesses. The compounding impact was experienced about 48 hours later with the downstream flooding that further paralyzed residents for several days.

Emerging hydrodynamic models can improve forecasting and help reduce uncertainty by projecting inundation overland rather than just water height at the shoreline. These models can incorporate combined effects of ocean storm surge, riverine discharge, tides, and winds to provide visualized forecasts of flooding and assist in better response planning. To explore this potential, Noblis, the Virginia Institute of Marine Science (VIMS), WFOs Wakefield and Sterling, Virginia, and CBOS through the NOAA Chesapeake Bay Office (NCBO) and the U.S. Geological Survey (USGS), agreed in January 2006 to an *ad hoc*, self-funded, collaboration. The objectives were to 1) rapidly develop an initial prototype system that integrates high-resolution atmospheric and hydrodynamic storm surge models, 2) evaluate the prototype's ability to predict land inundation in the Washington, DC area, 3) provide flooding results to EMs using emerging visualization technologies and evaluate improved methods, and 4) document what would be needed for an operational NWS prototype.

II. BACKGROUND

Storm surge and inundation by tropical (e.g., hurricanes) or extratropical (e.g., nor'easters) storms can profoundly affect coastal communities and ecosystems worldwide. According to U.S. Census data, more than 16 million people live in the Chesapeake Bay watershed and this trend continues to grow. Add the anticipated sea-level rise, continuing coastal development, and potential increases in the frequency and severity of storms possibly related to global warming [1], and the people of the Bay region and their property are facing ever increasing risks.

Response to these risks varies, but inner-coastal communities can be lulled by the idea that the extension of land seaward of enclosed bays and estuaries east of the Chesapeake Bay will protect inner-coastal residents and their property by blunting the power of waves and surges from storms that approach from the open sea. For some storm tracks, however, this same land extension can trap and even enhance surge height when combined with tides and storm-induced river flooding. In such cases, the illusion of protection instead leads to increased vulnerability. As was evident from the destruction in the Bay from Hurricane Isabel, the effectiveness of warnings and responses through EMs and first responders could be significantly improved by an operational, validated, end-to-end, inundation forecasting, visualization, and communications system.

To address these priorities and to mitigate the impacts, CIPS will provide two crucial pieces of information: (1) accurate prediction of storm surges and (2) high-resolution, visualized forecast of the location, depth, and duration of land inundation, as identified by EMs as major needs [2,3]. Current operational methods and the storm surge and inundation products do not adequately meet the requirements of EMs in all coastal communities. EMs and first responders are responsible for preparing communities for disasters and then responding to protect citizens and their property. NWS forecasters use a hydrodynamic model developed in the 1980's to predict tidal gage water-level heights and provide that information to EMs. The EMs rely heavily on local history to extrapolate in-water gage height predictions to their shoreline and then inland to estimate what land areas will flood. Although this approach enables some advanced decision-making on where to deploy (and not deploy) emergency responders and crews, the inundation extent, timing, and depth are often quite uncertain. Critical resources and time are expended deploying spotters and awaiting word for information as the storm unfolds. The EMs have indicated the urgent need for better local information about expected surge and inundation.

The CIPS team has as its goal to construct, evaluate, and deliver an end-to-end, prototype inundation forecasting system to facilitate emergency management decision-making in the challenging case of intricate coastlines comprised of semi-enclosed coastal bays and estuaries. These complex coastal features can either protect large population centers or render them vulnerable to trap and amplify storm surges, as was the case in the Bay with Hurricane Isabel. The accuracy of forecasts depends critically on small differences in the relative positions of the storm track and the Bay's axis that challenge current forecast models. CIPS is intended to improve the accuracy, reliability, and capability of flooding forecasts for tropical cyclones and non-tropical wind systems such as nor'easters. The initial prototype uses advanced modeling and visualization techniques to depict expected inundation at spatial resolution less than a city block (~50 m) and vertical resolution about thirty centimeters in time-step display of one hour or less. EMs' response to this prototype has been positive and supportive.

III. RAPID PROTOTYPE APPROACH

The intent of the rapid prototyping approach is to develop an initial capability that can be evaluated to see if it will generally meet user needs and then refine it into an operational prototype in collaboration with users, in this case initially, the EMs. CIPS will provide an end-to-end, quantifiable, storm surge and inundation forecast system prototype that defines users' needs and concept of operations; integrates subsystems for observation, forecasting, visualization, validation, data and product development; and communicates high-resolution products through WFOs to EMs and the public. CIPS is building on the initial prototype through an innovative, multi-model, ensemble-forecasting approach to predict combined effects of storm surge, tidal, and river flow inundation in the Bay and its tributaries with prediction uncertainty estimates.

WFOs Sterling and Wakefield, Virginia and Mt. Holly, New Jersey and WeatherFlow, Inc. will develop the atmospheric forecast ensemble with two models: the Weather Research & Forecasting (WRF) environmental modeling system and the Regional Atmospheric Modeling System (RAMS). These will be coupled with high-resolution Laser Image Detection and Range (LIDAR) topographic elevation data and the VIMS Unstructured grid Tidal Residual Inter-tidal Mud (UnTRIM) and Eulerian Lagrangian Circulation (ELCIRC) models and the University of Maryland Center for Environmental Science (UMCES) Regional Ocean Modeling System (ROMS) [5] hydrodynamic models. NOAA's Middle Atlantic River Forecast Center (MARFC) will provide river discharge forecasts from the Advanced Hydrologic Prediction Service (AHPS). Ensemble winds and water-levels will be validated with observations from CBOS-developed, integrated, and interoperable networks.

Noblis will create, and USGS will provide data to validate, Geographic Information Systems (GIS) visualizations and animations of the inundation ensemble with uncertainty in flood-prone areas. CBOS, through Old Dominion University (ODU) and CRC, will coordinate collaboration with WFOs and EMs to evaluate and refine CIPS' iterative development. UMCES will quantify the economic benefits of CIPS to enable EMs to better prepare for, respond to, and advise the public about potential surge and inundation. The result of this rapid prototyping process will be an operational prototype capability with clearly defined and validated requirements and concepts of operation to transition to a sustained, operational system.

IV. PROCEDURE

Creating CIPS requires an innovative, two-fold approach. First, the technique of ensemble forecasting is being augmented in the atmospheric domain and translated to the hydrodynamic and hydrologic domains. To expand the atmospheric ensemble, the WFOs Sterling, Wakefield, and Mount Holly, that provide forecast services to communities throughout the Chesapeake Bay, will partner with WeatherFlow, Inc. to produce parallel, high-resolution atmospheric forecasts for the Bay region within their operational schedule. To extend the ensemble to hydrodynamics, VIMS will partner with the UMCES Horn Point Laboratory to refine and combine their already successful models with the incorporation of stochastic hydrologic flow to produce high-

resolution, operational forecasting in the entire Bay region. The primary benefits are improved accuracies and the production of quantitative estimates of forecast uncertainties.

Second, CIPS development is exploiting a successful prototype visualization, validation, and information-delivery system for EMs, a technology developed, validated, and evaluated by a team of government, academic and industry CBOS partners. Part of this capability is a new, rapid deployment system of inundation sensors to deploy immediately before storms and thereby obtain direct measurements of water levels by the USGS. Noblis will work with WFOs and EMs to address their requirements and deliver the visual inundation information at city-block resolution at a variety of Chesapeake Bay sites. CBOS, through Old Dominion University and the UMCES Chesapeake Bay Laboratory, and Noblis will conduct a dynamic outreach program with EMs to integrate and assess the economic value of CIPS, not only for the immediate storm response by EMs, but also for their advance planning and decision-making during recovery. CIPS ultimately will provide an end-to-end system that defines users' needs, integrates the subsystems for observation, forecasting, visualization, validation, data and product development, and communicates high-resolution products through WFOs to EMs, and then to a broad spectrum of users, including the general public.

The Emergency Management Coordinator for the City of Alexandria, VA is a project partner and represents CBOS partners' ongoing engagement with EMs in other local and state EM agencies throughout the Chesapeake Bay area that will also participate in the EM user groups formed for CIPS. These EMs have seen the CIPS initial prototype and are ready to assist in its development. WFOs, as the primary users of CIPS, will deliver CIPS forecasts and conduct appropriate training in conjunction with CBOS, to fulfill their mission of providing operational forecasts. WFOs will incorporate CIPS products as appropriate into their existing forecast products and provide them to state and local EMs, the Federal Emergency Management Agency (FEMA) and other agencies. Ultimately, CIPS' users are citizens, chiefly living in coastal communities. CIPS education and outreach efforts will communicate the value of CIPS to the public welfare.

CIPS initially will be constructed as a working operational prototype for the Chesapeake Bay region, but it will be built for efficient transfer to the broader MACOORA and other Regional Associations (RAs) within IOOS. Inundation support to EMs is the focus of CIPS, but as it develops, its audience will extend to those addressing additional IOOS societal needs, including maritime operations, national and homeland security, public health risks, maintaining healthy coastal ecosystems, and sustained use of resources.

To meet the challenges above, prototype capabilities for atmospheric and hydrodynamic modeling and visualization of storm surge and inundation in the Chesapeake Bay have been developed and have proven to be extremely promising [4-14]. These prototypes demonstrate the ability to model storm surge and inundation in a hindcast mode with high resolution in the Bay and the tidal, upper Potomac River and to visualize the results in a way that will be very useful to EMs. Building on this capability, CBOS partners propose to develop an operational prototype CIPS.

CIPS will employ an innovative, multi-model, ensemble-forecasting approach to predict the combined effect of storm surge, tide, and river flow inundation in the Bay and its tidal tributaries and provide an estimate of the uncertainty of the prediction. To communicate ensemble forecasts effectively, CIPS will exploit advanced GIS techniques to visualize projected flooding with uncertainty to EMs through the existing services of the WFOs. It is expected that CIPS will significantly enhance WFO forecasts, and hence the EMs' capability to prepare and respond to storm surge and inundation. To achieve and measure improvement, WFO and EM staff will be engaged from the outset to advise, evaluate, and refine CIPS for their use and to communicate the improved storm-surge information effectively. EMs will provide information to CBOS partners to conduct an economic evaluation of CIPS. Ultimately, CIPS will quantifiably improve the capability of federal, state, and local EMs to prepare for, respond to, and advise the public about potential surge and inundation in their communities.

A. Hydrodynamic Modeling of Storm Surge and Inundation for Coast-Bay-Estuary

VIMS scientists have developed an unstructured grid model with an efficient solver to simulate storm surge and inundation throughout the CB [4-7]. The storm surge code, ELCIRC [8], reflects a three-dimensional unstructured grid model formulation

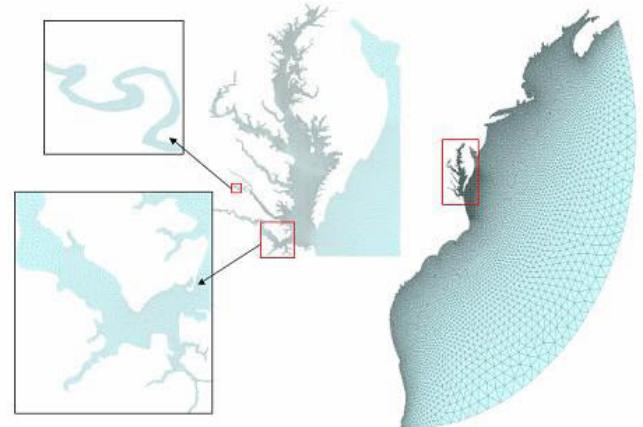


Fig. 1 ELCIRC grid: Chesapeake Bay and Atlantic Coast.

[9] (available as open source at <http://www.ccmlr.ogi.edu/>). The limited domain, which uses a derived open boundary condition that utilizes coastal observations [10], was successfully applied in the Chesapeake Bay for hurricane simulation. In this project, the domain will be further expanded in the offshore and along shore directions. For example, a 450,000-cell grid will be used for Bay modeling, with 120,000 cells for Bay waters, 300,000 cells for the inter-tidal zone, and 30,000 cells for the coastal ocean extending 1000 kilometers offshore from Nova Scotia to Florida, as the outer open boundary (Fig. 1). Preliminary storm surge predictions made with this grid and the ELCIRC model have been validated against observed water levels for Hurricane Isabel (Fig. 2) for the peak surge and subsequent flooding due to river discharge, as a complete inundation profile including timing and phases. The model also simulated wind-induced set up in the Upper Bay as storm surge propagated northward. R-squared correlation coefficients exceeded 0.8; maximum errors were less than 15 centimeters. Comparable results were obtained for Tropical Storm Ernesto (9/06).

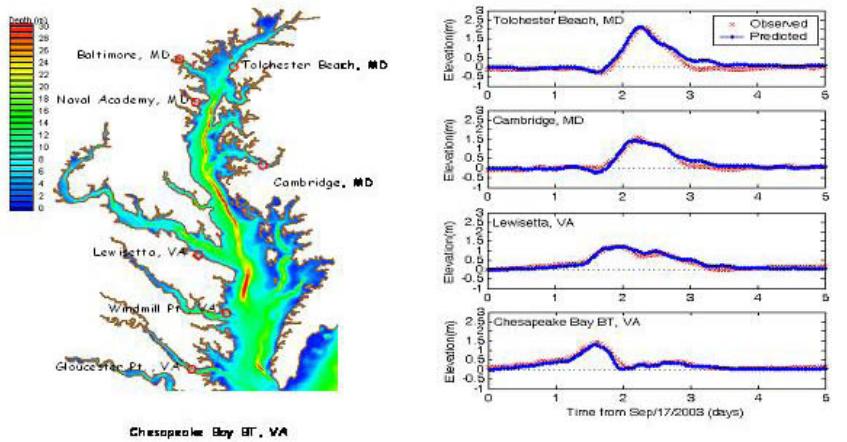


Fig. 2 ELCIRC validation for Hurricane Isabel (a) gage location; (b) observed (red) vs predicted (blue) water levels.

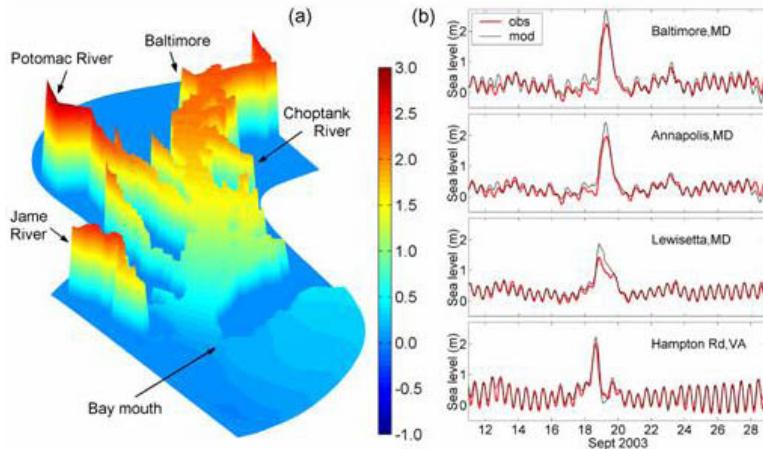


Fig. 3 ROMS validation for Hurricane Isabel: (a) 3D peak water levels at high storm surge; (b) observed (red) vs predicted (black) water levels.

0.96; while the RMS error for predicted current was about 0.19 meters per second with a predictive skill of 0.93.

B. Modeling Overland Inundation with High-Resolution Grids

ELCIRC uses high-resolution grids (order of tens of meters) and predicts flooding of urban areas due to storm surges, tides and river flows. The grid for Washington, DC (Fig. 4) resolves details such as river shorelines, highways, islands, and buildings (Pentagon). Topography (high resolution LIDAR data) provides digital elevation. The predicted Maximum Envelope of Water (MEOW) map for Alexandria, VA during Hurricane Isabel, discussed later, showed simulated flooding on a city-block scale and demonstrated ELCIRC's potential to produce fine-scale inundation forecasts for the Bay [4].

ROMS uses orthogonal structured grids. To forecast inundation for a specific geographic area requires either nesting a high-resolution local model to the coarser-resolution Bay-wide model or employing the GRIDGEN technique developed at CSIRO for estuaries and coastal oceans (<http://www.marine.csiro.au/~sakov/>) [15]. The GRIDGEN technique provides the ROMS model with flexibility similar to that of an unstructured grid model.

UMCES scientists have used ROMS to develop a hydrodynamic model for the Chesapeake Bay [11]. This model is forced by open-ocean sea levels, river-flows, winds, and heat exchange across the water surface. ROMS-CB has been validated against a variety of observed data including (1) water-level elevations and tidal currents at Bay gage stations, (2) salinity and temperature time series at stations maintained by the U.S. EPA Chesapeake Bay Program, (3) real-time current velocities from selected CBOS buoys, and (4) three-dimensional synoptic salinity maps from hydrographic surveys [11-14]. ROMS was coupled to a regional atmospheric model MM5 (<http://www.atmos.umd.edu/~mm5>) to predict the storm surge from Hurricane Isabel (Fig. 3) and the associated wind-driven currents [13-14]. Averaged RMS error for predicted water levels was 13 centimeters and the predictive skill reached a score of 0.96.

C. Coupling with Atmospheric Models

Winds play a dominant role in driving storm surges but are difficult to predict in coastal areas. Banding structures in tropical systems are especially difficult to predict. The Chesapeake Bay topography is complex. Large contrasts in wind speeds are observed between land and water surfaces. Currently, the operational model from the NOAA National Centers for Environmental Prediction (NCEP) has a horizontal resolution of 12 kilometers which is inadequate for resolving detailed wind fields over the Bay and its tributaries. Therefore, a high-resolution atmospheric model is required to provide detailed surface winds. Ensemble forecasting of weather, including winds, has been shown to improve forecasts and provides a means of conveying uncertainty [16]. Therefore, a multi-model (WRF and RAMS), multi-boundary conditions approach will be used to obtain a series of wind fields with increasing resolution. The tandem use of WRF and RAMS will provide a range of potential wind fields.

The WFO Wakefield (AKQ) will run a high resolution WRF model, which is a complete numerical weather prediction system tailored for a workstation for a specified local modeling domain (Fig. 5). AKQ has configured this model to run at approximately 4 kilometers horizontal resolution, using either the NCEP non-hydrostatic mesoscale model core (NMM) or the advance weather research core (ARW) that was developed by the National Center for Atmospheric Research. This model is state-of-the-art with configurable parameters and the resolution to provide the best forecast for the Bay. The local WRF will use the NMM core at 4 kilometers resolution. This grid allows the model to run with explicit convection. Consequently, the model is able to produce detailed banding structures in tropical systems and wind-field changes at fine scales. The RAMS is a high-resolution numerical model that has been run operationally at WeatherFlow for over three years and is a well-established, mesoscale model. RAMS was developed at Colorado State University and uses a different numerical core and physics package from WRF. Given RAMS is run at 2 kilometers horizontal resolution (versus 4 kilometers for WRF), it may resolve additional mesoscale features of the winds in the Bay region.

Initially AKQ WRF and RAMS will run within a 12-hour forecast cycle, at 0000 UTC and 1200 UTC for a 7-14 day period, and possibly within a 6-hour forecast cycle later in the development of CIPS. In either case, one run of both models will use the Global Forecast System (GFS) initial and boundary conditions, and a second run will use the North American Mesoscale model (NAM) initial and boundary conditions. The NAM (12-kilometers) and GFS (~32-kilometers) also will be run, creating an ensemble of six surface wind and pressure (atmospheric) fields. This ensemble approach frequently is used in meteorological forecasts and has been shown to produce more accurate forecasts than individual model runs. The six-field atmospheric ensemble will drive each hydrodynamic model, creating a 12-hour 12-ensemble forecast of storm surge and inundation in the Bay and its tidal tributaries.

D. Coupling with Hydrologic Flow Model

Intense rainfalls often accompany hurricanes, tropical storms and nor'easters. Consequently, inundation in tidal estuaries can be caused by a combination of storm surge (propagating upstream) and river runoff (discharging downstream). Simulations of Hurricane Isabel in the upper Potomac River induced a second flooding peak beginning about 1.5 days after the peak storm surge. Hurricane Isabel was a relatively dry storm; conversely, for a wet storm such as Hurricane Floyd in 1999, heavy precipitation can significantly contribute to flooding, particularly in the upper reaches of the Bay tributaries. Therefore, the ELCIRC and ROMS models will incorporate runoff forecasts from NOAA's Advanced Hydrologic Prediction Service (AHPS).

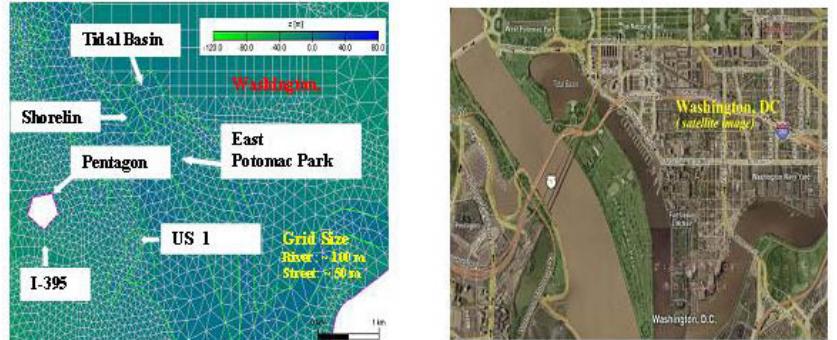


Fig. 4. ELCIRC quadrilateral and orthogonal triangular grid for Washington, DC (left); corresponding satellite image (right).

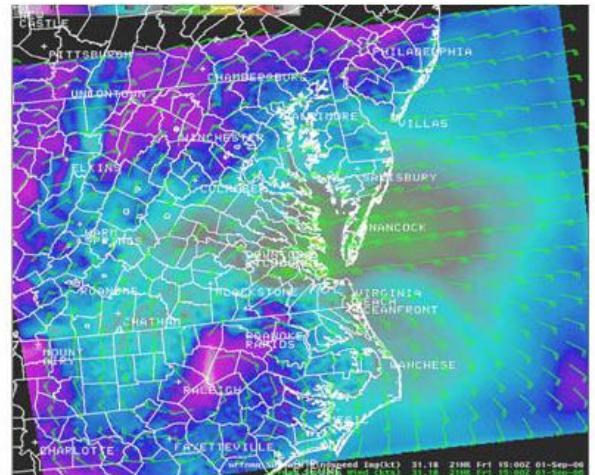


Fig. 5. WRF Tropical Storm Ernesto wind forecast.

The advantages of AHPS are: (1) hydrologic model characteristics are determined for each local river watershed and each tributary with increased forecast accuracy, (2) probabilistic forecasting with ensemble prediction offers a scientifically sound and practical methodology for increasing forecast lead time, and (3) in terms of interoperability, AHPS has been promoting an increase of distribution of products using advanced information technologies (e.g., internet); therefore, it provides broader and more timely access. In the early stage of this development, USGS observed stream flow from Bay tributaries will be used with historical storm surge events. For the following development, the predicted ensemble stream flow from AHPS will be tested and utilized. AHPS's emphasis on Ensemble Stream-flow Prediction (ESP), which can provide a suite of ensembles for lead times from one hour to days, is consistent with the CIPS approach. The use of AHPS forecasting could potentially reduce the uncertainty in forecasting river flow and provide a critical tool for appropriate cost-benefit analysis.

E. Historic Ensemble Forecasting and Data Assimilation

To develop a robust ensemble prediction system, validation exercises will be conducted using three recent storms that exerted strong impacts on the Chesapeake Bay. They include Hurricane Isabel, the extratropical storm that evolved from tropical storm Ernesto in 2006, and one nor'easter in November, 2006. In addition to simulating storm surge throughout the Bay, CIPS will simulate and visualize overland flooding for three high-risk and flood-prone Bay subregions — the upper tidal Potomac River (including Washington, D.C.), the Virginia Beach to Hampton Roads inner coastal region (including Norfolk), and the eastern shore of the Delmarva Peninsula (including Dorchester and Talbot Counties, MD). Each area is served by a different WFO and offers variations in EM concerns related to the demographic nature of the communities. For each storm event, wind and pressure forecasts will be quantitatively compared to the measurements collected at multiple weather stations (~18-24 locations) located inland, on the water, or in the land-water transition zone throughout the Bay. Although skill metrics, such as bias and RMS error, will be used, they are insufficient to validate the predicted wind and pressure fields. These statistics may fail to account for time continuity of the modeled solution and are sensitive to small displacements in time and/or space. For example, numeric skill scores may indicate higher errors for models that correctly determine whether or not onshore flow will occur, but fail to time its onset or abatement (e.g., sea breeze). Therefore, both a thorough in-depth subjective analysis and a prescribed set of performance statistics will be used to determine which modeled field best reflected the observed conditions.

Similarly, water-level predictions from the hydrodynamic models will be compared with observed levels at 18-24 tidal-gage stations located throughout the Bay region. The RMS and relative errors, correlation coefficients, and the skill score will be calculated to assess each model's predictive capability. In addition, some model runs will be conducted in 3-dimensional mode to validate against current measurements from CBOS buoys. Historical CIPS ensemble results will be evaluated to determine whether the ensemble can be reduced in scope in relation to wind and pressure fields, or otherwise modified, to enable future ensemble runs within a 6-hour forecast window. CBOS will archive all model outputs, observational data, and validation results.

F. Real Time Ensemble Runs with Overland Flooding Validation

As the development progresses, the CIPS prototype will transition to run in real-time. Depending on the outcome of historical ensemble runs, the ensemble forecast window could be reduced to a WFO standard 6-hour window. Modeled wind and pressure fields and related meteorological observations will be provided to CBOS. CBOS simultaneously will collect and provide water-level observations from stations throughout the Bay and nearby coastal ocean boundaries. Local areas in the Bay subregions, described earlier, will be chosen for an overland inundation network to be designed by the USGS in collaboration with Noblis and EM partners, and then implemented to obtain actual observations of overland flooding should a likely storm-surge inundation event occur [17]. Each local network will provide event-based, time-series data of the observed water levels at multiple (~12) locations to compare to predicted and visualized water levels. Ideally, validation of storm surge and local overland flooding will be captured for at least two events (tropical storm or nor'easter) in the Bay and in each local area, respectively. In addition, should a significant hurricane be expected to track into the Bay during the CIPS project, the national USGS Storm Surge Program will deploy additional sensors throughout the Bay shoreline to provide additional broad-scale indications of overland flooding.

As CIPS development continues, and if an actual significant real-time event occurs, efforts will be made to model this event, and have the NWS and EMs conduct an exercise for all three Bay subregion inundation areas around this remodeled storm. If no real-time event of significance occurs, a synthetic storm will be designed and used for this exercise. Regardless of whether an extreme storm occurs, creation of an operational prototype forecast system capability that routinely provides observational data for ensemble modeling is a major objective of the CIPS development. Achieving this objective will define the role of CBOS partners going forward with ultimate deliverance of an operational prototype modeling capability to the NWS, and of the required CBOS observing system to support this capability.

G. Data Assimilation

If the given wind field and offshore sea-level boundary condition are accurate, storm-surge models typically can produce good predictions without assimilating sea-level data. In practice, however, wind and offshore sea level data contain errors. Given that

CBOS actually measures real-time sea level, their assimilation will be explored. Various approaches have been proposed for ocean data assimilation which could be divided into two major categories. First, data are assimilated into dynamical models in an *ad hoc* pragmatic manner designed to nudge the model toward the data with various forms of optimal interpolation [18]. Then, formal estimation and control theory is applied to the use of the observed data using an objective approach to minimize data-model misfit under the constraint of the model dynamics. Objective approaches include the adjoint method and Kalman filter and smoothing [19]. Given the pros and cons of these two approaches, ELCIRC will use the pragmatic approach. ROMS has incorporated a multivariate, intermittent Optimal Interpolation (OI) scheme in which observations and model data are melded together taking into account errors in the observations and prediction. This data assimilation method is very efficient and inexpensive and will be used to assimilate CBOS sea-level measurements into the hydrodynamic model. Predictions between the assimilation and non-assimilation model runs will be compared, and the cost-effectiveness of this data-assimilation technique in storm-surge prediction will be evaluated.

H. GIS Visualizations of Water Level and Overland Flooding for Operational Products

Prototype development has demonstrated that the storm-surge inundation output from the hydrodynamic model can be visualized to show the location, depth, and duration of inundation in static and animated products that can depict inundation at the city-block level (Fig. 6). Regional EMs have seen the prototype and stated that this is the type of capability they would like to have. CIPS will develop the prototype visualization capability to encompass the ensemble forecast predictions and uncertainty. Inundation visualizations will include static images and animations with the uncertainty. Overland inundation visualization will be at a spatial resolution of less than a city block (~50 m), vertical resolution of less than one foot (~30 cm or less), with a sequential time step of one hour or less. The best available spatial elevation data (preferably high-resolution LIDAR) and GIS layers will be used to visualize overland inundation for at least one local area in each of three high-risk flood-prone subregions identified with state and local EMs. Validation of visualized overland inundation will be conducted with a portable, rapidly deployed system of on-land water-level sensors in at least one local area if storm events occur during the development of the CIPS prototype. Processing time to produce static or animated visualizations of inundation forecasts will be reduced to operate within the initial 12-hour, and possibly 6-hour, NWS forecast cycle by automating current manual operations, using parallel processing and other techniques, and optimizing model grids to reduce processing steps to develop the visualization products.

CIPS visualization products will be compatible with regional EM information systems, such as the Emergency Management Mapping Application (EMMA) developed for the Maryland and Virginia EM state agencies. CIPS products will be developed within the Open GIS Consortium (OGC) Web Map Services (WMS) standard and will be compliant with the Federal Enterprise Architecture (FEA) initiative that standardizes GIS file formats compatible with ESRI (ArcGIS 9.2) products to facilitate easier exchange and use of GIS data files by local jurisdictions. A potential operational system that includes products for applications (e.g., Google EarthTM, Microsoft Virtual EarthTM, and Really Simple Syndication (RSS)) to deliver needed information required to support current decisions, while managing a broad spectrum of data, also will be investigated. CIPS is planned to result in a prototype warning system for NOAA, CBOS, MACOORA and other agencies that could transition to sustained operations in the Chesapeake Bay and be replicated around the Nation's coastal and Great Lakes regions.

V. CBOS-MACOORA-IOOS OBSERVING SYSTEM AND DATA MANAGEMENT

CIPS will have strong support from CBOS as a distributed data center featuring data providers from all of the institutions around the Chesapeake Bay. The NOAA Chesapeake Bay Office (NCBO) operates the CBOS data management system (DMS). Due to the variety of data needed to run and evaluate the coupled atmospheric and hydrodynamic system, identification of the archived data and the requisite observation data is a major task. After identification of assimilation or validation gage observation locations, multiple point time series can be extracted. Spatial data, such as grid-based atmospheric wind, pressure fields, and LIDAR data needed for input into the model will be interpolated automatically through CBOS (via NCBO server). All identified observational and model data will be provided in a manner compliant with IOOS Data Management and Communications (DMAC) guidelines. In accordance with specific DMAC guidance at national or regional (MACOORA) levels, CBOS-NCBO will identify a common and consistent DMS including standards for the data and data delivery. In addition, observational and

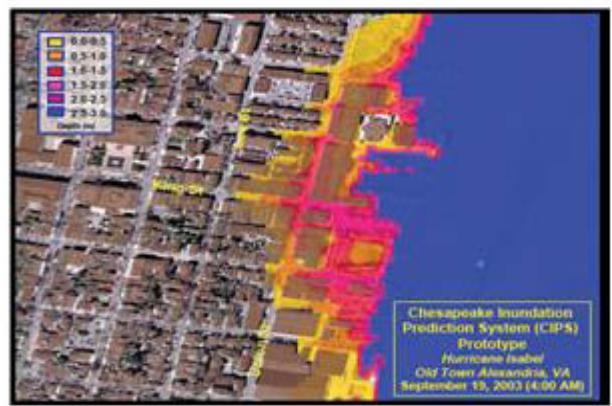


Fig. 6. Static visualization of peak inundation flooding during Hurricane Isabel.

modeled data will be provided with standard and consistent parameter nomenclature, units of measure, and temporal and spatial reference datum.

VI. BENEFITS

The users of CIPS information include local, state, and federal EM and related organizations; utilities (infrastructure); transportation and shipping entities; property owners; broadcast media and the general public. These users will benefit from high-resolution predictions of water level and over-land inundation. EMs have stated that such information would greatly improve their preparation for, response to, and recovery from flooding events [3-4]. An EM User Group will be established to provide ongoing product requirements. The value of the improved information available will be quantified. CIPS information will be delivered to users through current NWS operations and existing EM systems. CIPS will contribute to IOOS by using CBOS as an important source of system data. CIPS development includes identifying observing requirements for improving and expanding CBOS and other regional observing systems that supply data to CIPS. CIPS also will serve as a prototype for other regions to develop a similar capability for inundation forecasting, which will help define national IOOS observing requirements to support such regional capabilities.

A. Quantification of Economic Benefits

CIPS improvements to the accuracy and reliability of flooding forecasts are expected to generate benefits that are measurable in terms of reductions in deaths, injuries, and human hardship and avoidance of property damage and other economic costs. The extent of these benefits will depend on how different end-users utilize CIPS forecasts to improve preparations for and responses to flooding events. Quantifying and monetizing these benefits is a three-step process. First, determine how citizens and EMs respond to and use inundation forecasts they receive now and how they perceive or measure resultant benefits. Second, determine how the improved CIPS information will increase the effectiveness of their responses and these benefits. Third, quantify differences between expected response benefits with and without improved CIPS information.

Tracing and measuring the pathways of benefits to apply this three-step approach in a selected subregion requires estimating the value of assets at risk in inundation zones and working with decision-makers to understand their use of information to prepare for and respond to storms. Particularly important are: (1) the amount of effort (e.g., equipment and man-power) expended to determine flooding conditions in a specific area, (2) the information and criteria that EMs use to deploy resources to different areas at different times in the absence of CIPS; and (3) how increased confidence in flooding predictions influence EM decisions (Fig. 7). CIPS inundation forecasts have the potential to provide users a high level of confidence in flood forecasts compared with existing models and methods. The improved response effectiveness that results from more precise and understandable forecasts is the basis for tracing and quantifying the benefits. Benefit quantification will first be based on an assessment of information about historical inundation events and will then be refined using information about real-time events. The overall approach is expected to include location-specific methods for quantifying improved outcomes from applying CIPS forecasts, and the application of standard monetization methods to assign dollar value, for example, to measures of property damage and emergency and medical costs avoided, statistical lives saved, and reductions in business losses and household costs.

B. Outreach, Education, and Workforce Training

The Chesapeake Bay is an ideal “natural laboratory” for federal, state, and regional partners to work together to improve the tools used by coastal and emergency managers to make educated and timely decisions that can mitigate damage due to coastal storms, and enhance community resiliency to such events. A better-informed citizenship is able to better prepare and be safe during flooding events that accompany coastal storms and hurricanes. The CIPS project directly supports NOAA’s vision of “*an informed society that uses a comprehensive understanding of the role of the oceans, coasts and atmosphere in the global ecosystem to make the best social and economic decisions.*” CBOS through ODU will facilitate the coordination of existing facilities, infrastructure, and communications networks to help the NWS prepare local EMs and the general public for storm-induced flooding and overland inundation. The goal is to reduce the risk of hazards through stronger partnerships and alliances.

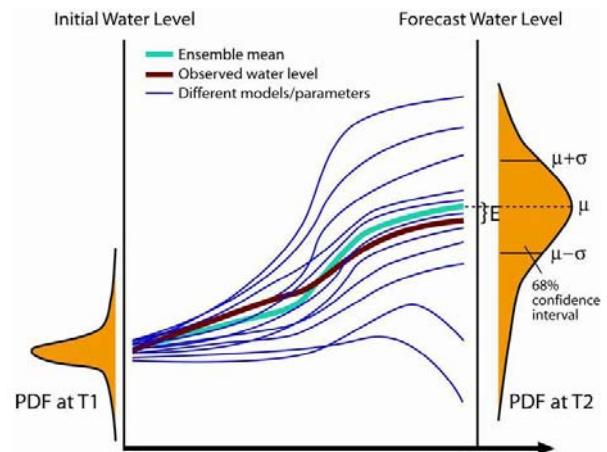


Fig. 7 At a Gage Forecast: Ensemble mean water level with estimated uncertainty as nowcast (T1) and forecast (T2). Ensemble results improve confidence of Emergency Managers to better plan and execute responses before, during, and after an inundation event which provides net economic benefits.

Specifically, CBOS is working with the WFOs to develop an Emergency Manager User Group (EMUG) consisting of EMs throughout the Chesapeake Bay region. Through the EMUG, CBOS and the WFOs will provide training to EMs for the use of CIPS visualizations and forecasts. EMs can provide unique and invaluable feedback to the CIPS development team to meet EM specific needs and produce optimum products. EMs can also provide specific feedback as to how these improved inundation prediction products will cause changes in their operations, which in turn will result in tangible benefits to life and property.

VII. BROADER APPLICATIONS AND FUTURE DEVELOPMENT

CIPS will develop broader capabilities to assess efficacy of planned mitigation (*e.g.* seawalls and breakwaters), planning for projected sea-level rise, and, possibly, expected inundation from tsunamis. CIPS is being constructed initially as a Chesapeake Bay prototype with planned efficient transfer to MACOORA and other IOOS Regional Associations. This approach complements the NOAA Storm Surge Partnership Project by focusing on large, complex, coast-bay-estuary systems. Inundation is the initial focus, but the prototype can be applied to additional IOOS societal goals, including maritime operations, national and homeland security, public health risks, maintaining healthy coastal ecosystems, and sustained use of resources.

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